UNIVERSITY OF CALIFORNIA, SAN DIEGO

Spatial and Temporal Scales of Precipitating Tropical Cloud Systems

A dissertation submitted in partial satisfaction of the

requirements for the degree Doctor of Philosophy

in

Oceanography

By

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The dissertation of Eric Wilcox is approved, and it is acceptable in quality and form for publication on microfilm:

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Chair

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for Erin

TABLE OF CONTENTS

LIST OF SYMBOLS

B_λ	blackbody emission (W m^{-2} str^{-1} m^{-1})
C	speed of light (2.998×10^{8} m s^{-1})
C_l	longwave cloud radiative forcing (W m^{-2})
C_s	shortwave cloud radiative forcing (W m^{-2})
E	evaporation rate (kg kg^{-1} s^{-1})
$\dot{E}$	evaporation rate (kg m^{-2} s^{-1})
F	longwave flux at top-of-atmosphere (W m^{-2})
F_{clr}	clear-sky longwave flux at top-of-atmosphere (W m^{-2})
F_c	grid cell fraction containing cloud
F_p	grid cell fraction containing precipitation
F_{cp}	grid cell fraction containing cloud and precipitation
f_{240K}	fraction of cloud area with IR brightness temperature less than 240K
G	coefficient for infrared rain estimate (mm hr^{-1})
h	Planck constant (6.626×10^{-34} J s)
I	radiant intensity (W m^{-2} str^{-1} m^{-1})
k	Boltzmann constant (1.381×10^{-23} J K^{-1})
k_E	coefficient of rain evaporation
L	condensed water amount in grid cell (kg m^{-2})
L_c	condensed water amount from convection (kg m^{-2})
L_c	condensed water amount from stable condensation (kg m^{-2})
L_v	latent heat of vaporization (J kg^{-1})
LH	latent heating and latent heat flux (W m^{-2})
n	aerosol mixing ratio (kg kg^{-1})
$\dot{P}$	production rate of precipitating water in grid cell (kg m^{-2} s^{-1})
$\dot{Q}$	net production rate of precipitating water in grid cell ($\dot{P}$ - $\dot{E}$; kg m^{-2} s^{-1})
$\dot{Q}_c$	net production rate of precipitating water from convection (kg m^{-2} s^{-1})
$\dot{Q}_{sc}$	net production rate of precipitating water from stable condensation (kg m^{-2} s^{-1})
RH	relative humidity
R	rate of production of precipitation (kg kg^{-1} s^{-1})
R_s	surface rain rate (mm hr^{-1})
S	solar flux (W m^{-2}), also radiant source term (W m^{-2} str^{-1} m^{-1})
SH	sensible heat flux (W m^{-2})
T	temperature (K)
T_{IR}	METEOSAT-5 infrared window channel brightness temperature (K)
T_{WV}	METEOSAT-5 water vapor channel brightness temperature (K)
α	albedo, also extinction coefficient (m^{-1})
α_{clr}	clear-sky albedo

λ	wavelength
ρ_w	density of water (kg m^{-3})
CCM3	Community Climate Model version 3
CEPEX	Central Equatorial Pacific Experiment
CERES	Clouds and the Earth's Radiant Energy System
CRF	cloud radiative forcing
ERBE	Earth Radiation Budget Experiment
GATE	Global Atmospheric Research Program Tropical Experiment
GCM	general circulation model
INDOEX	Indian Ocean Experiment
IR	infrared
ITCZ	Inter-tropical Convergence Zone
MATCH	Model for Atmospheric Transport and Chemistry
MCS	mesoscale convective system
MPF	mesoscale precipitating feature
NCAR	National Center for Atmospheric Research
SSM/I	Special Sensor Microwave Imager
TOA	top-of-atmosphere
TRMM	Tropical Rainfall Measuring Mission
TMI	TRMM Microwave Imager
WV	water vapor

LIST OF FIGURES

LIST OF TABLES

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The text of chapter three, in full, is a reprint of the material as it appears in the Journal of Climate. I was the primary researcher and author, and the co-author, V. Ramanathan, directed and supervised the research that forms the basis for this chapter. The text of chapter four, in full, is a reprint of material that has been accepted for publication to the Journal of Climate pending revision. I was the sole researcher and author of this publication.

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PUBLICATIONS

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Wilcox, E. M. and V. Ramanathan, "Scale Dependence of the Thermodynamic Forcing of Tropical Monsoon Clouds: Results from TRMM Observations", Journal of Climate, vol. 14, pp. 1511-1524, 2001

Hellman, F., M. Q. Tran, A. E. Gebala, E. M. Wilcox and R. C. Dynes, "Metal-Insulator Transition and Giant Negative Magnetoresistance in Amorphous Magnetic Rare Earth Silicon Alloys", Physical Review Letters, vol. 77, pp. 4652-4655, 1996

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ABSTRACT OF THE DISSERTATION

Spatial and Temporal Scales of Precipitating Tropical Cloud Systems

By

Eric Martin Wilcox

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Professor V. Ramanathan, Chair

Precipitation, radiative forcing, and aerosol scavenging in tropical cloud systems over the wintertime Indian Ocean are examined in satellite observations and global atmospheric simulations. Measurements of surface rain rate and top-of-atmosphere radiative fluxes from the TRMM satellite, as well as brightness temperature measurements from the METEOSAT-5 satellite, are used to identify the boundaries of cloud systems, track their evolution, and determine the spatial and temporal scales of cloud thermodynamic forcing. The resulting quantitative, statistical description of monsoonal cloud systems is compared with simulated cloud systems in the NCAR CCM3 model.

Monsoonal clouds span a spectrum of spatial scales from smaller than 25 km^2 to greater than 10^7 km^2. Atmospheric heating owing to precipitation and the cloud greenhouse effect, as well as surface cooling owing to cloud albedo, increases with the spatial scale of cloud systems. As a result, thermodynamic forcing of the monsoonal environment is dominated by the contribution from giant semi-permanent decks of overcast cloud that

persist for days to weeks. Embedded within such cloud decks are numerous rain cells reaching up to 1 million square-kilometers because deep convection organizes into clusters of narrow overturning cells attached to a broad stratiform region of precipitation. A relatively few such mesoscale convective systems are greater than 10^5 km^2, yet are responsible for up to 70% of monsoonal precipitation. In contrast, simulated cloud systems in the model gently precipitate throughout their duration and everywhere within their boundaries. The model lacks a process that acts to organize convection into mesoscale episodic structures.

Precipitation is the principal means by which particulate pollution is removed from the atmosphere. The effect of model biases in the distribution of precipitation is tested by integrating satellite precipitation measurements into the MATCH chemical transport model. Mesoscale convective systems in the equatorial Indian Ocean are a substantial barrier to the transport of aerosols from South Asia to the Southern Hemisphere. Using observations of the spatial coverage of precipitation in the model reduces the amount of South Asian aerosol transported to the remote Northern Hemisphere by more than a factor of 2 compared to a simulation using model derived precipitation.